Destabilization of Non-premixed Lifted Flames by Low Amplitude Acoustic Perturbations

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1 Introduction

The sensitivity of flows to acoustics is at the origin of combustion instabilities in many systems (Candel 1992). Understanding these instabilities, generally coupled with turbulence, is essential for burner design. Among these systems, non-premixed lifted flames are commonly found in industrial processes. Indeed,the jet dynamics depends on the development of aerodynamic instabilities and is very sensitive to the least perturbation. Thus, organized unsteadiness of air and fuel flow may occur, either voluntarily when control, of vortex shedding by acoustics for example, is imposed, or involuntarily when an uncontrolled oscillation coupling develops. As unsteady acoustic forcing acts on the jet behavior, acoustics will influence flames too. But the physical mechanisms involved in such unsteadiness of the combustion process are not well understood. This leads to several investigations with imposed oscillations. Hardalupas and Selbach in their review (Hardapulas and Selbach 2002) insisted on the fact that much work has to be done to understand the combustion control in pulsed combustors, the more so as the underlying mechanisms driving uncontrolled combustion oscillations and pulsed combustors are similar.

Baillot and Demare (2002 and 2003[a]) have found and classified the different responses of a non-premixed flame, stabilized in its hysteresis conditions, to acoustic excitations, in six typical zones. In particular, the jet can respond as an amplifier to a broadband of frequencies composed of its most amplified frequency, f_n and that of the jet column modulation, also called preferred frequency f_p. The organization of the jet can be enhanced by forcing it acoustically, in this spectral broadband and in the vicinity of their harmonics. This better organization in such a "resonant zone" improves the lifted flame stability by simultaneously decreasing its lift-off height and the fluctuations of the latter one, and avoiding any reattachment to the burner. On the contrary, in the zone defined as the "thin flame zone" by Baillot and Demare (2002), for frequencies higher than those of the resonant zone (except harmonic values of the natural frequency), acoustics disturbs the liftoff stability even for very low amplitudes of the forced jet modulation, typically with the same order of magnitude as the natural turbulence intensity. This work aims to highlight reasons for the "thin flame". A physical mechanism will be proposed to explain how low amplitude acoustic perturbations are able to drive destabilization of a non-premixed lifted flame.

2 Experimental facility

2.1 Measurement techniques

The flame is fed with a methane jet and ambient air. Four techniques are used to investigate the flow properties: high speed laser tomography, high dynamics laser tomography, Laser Doppler Anemometry (LDA) and Particule Image Velocimetry (PIV). LDA measurements are ensured by a continuous laser Argon-ion 4 W, 515 nm. The sampling time is adapted to the frequency to meet the Shanon conditions in full. The tomography system is composed of the same laser as LDA and a digital camera Kodak Ektapro at 9000 images/s. The jet is filmed in vertical and horizontal planes. An ICCD camera Princeton Instruments (16 bits) is used to measure mixture fraction by the Mie scattering technique. PIV is performed with a double-pulse ND:YAG laser. Velocities are measured in longitudinal and transverse planes inclined at an angle of 21^o from the horizontal plane. Methane and/or ambient air are seeded with olive oil dropets. A coflow (speed <5 cm/s, diameter: 200 mm) ensures the air seeding.

2.2 Burner

The burner consists of a vertical cylindrical tube with a 62 mm diameter followed by a convergent nozzle. Its exit nozzle diameter, d_0, has a lip smaller than 0.5 mm. The contraction is profiled to obtain a well-organized jet with a "top-hat"-shaped mean axial velocity U_0-profile and very low axial fluctuations U^{n0}_{rms} ($<$ 0.5 m/s) at the burner exit (z=0.7 mm). Honeycombs and grids provide a homogeneous flow. The fuel jet can be forced by a loudspeaker fixed at the bottom of the burner and driven by a sine-wave function generator.

2.3 Experimental conditions

Flame and jet features, and stabilization mechanisms with and without acoustics have been observed for diameter d_0 (4 - 10 mm) and flow rate (9 - 34 l/min) conditions. The conditions have been adjusted to maintain the stabilization in the hysteresis zone (Reynolds numbers: 3000-6000). This work was presented in (Demare and Baillot 2003[a]) as charts representing the responses of the excited flame to the forcing frequency, ranging from 2 Hz to 3000 Hz, and to the fluctuation amplitude of the perturbation, quantified by the axial vertical rms velocity at the burner exit (z=0.7mm), U^0_{rms}. It verified the robustness of the flame behaviors, previously found and classified in six zones for the given experimental conditions presented in (Baillot and Demare 2002). In particular, the "thin-flame" response is observed for U^0_{rms} having the same order of magnitude as the unforced turbulence amplitude, U^{n0}_{rms}.
Here, the phenomenon is illustrated by results obtained for the fixed exit conditions defined in (Baillot and Demare 2002): d_0= 6 mm and the lip smaller than 0.2 mm; without acoustics U_0=13.5 m/s and U^{n0}_{rms}=0.1 m/s at the burner exit (z=0.7 mm); with acoustics f_e=2600 Hz and the perturbation amplitude U^0_{rms}=0.3 m/s, only third U^{n0}_{rms}.

3 Aspect and stability of the flame

The unexcited flame, globally similar on the whole to a non-premixed turbulent lifted flame, has a particular base, composed of three or four separated lobes; its most probable liftoff height, H^n/d_0=3 is relatively small compared to that of fully turbulent flames and shows weak fluctuations H^n_{rms}/d_0=0.3. At 2600 Hz the plume of the lifted flame and its lobe-shaped base are analogous. But its base radius is smaller and its liftoff height H/d_0 is reduced to the most probable value of 2.3 with H_{rms}/d_0 unchanged. Moreover, the liftoff is very unstable insofar as the flame reattaches permanently to the burner after a few seconds of forcing. This loss of stability is explained by particular features of the jet imposed by acoustics, even at very low amplitudes.

4 Evolution of eddy structures

Eddy structures are visualized by high speed tomography images.

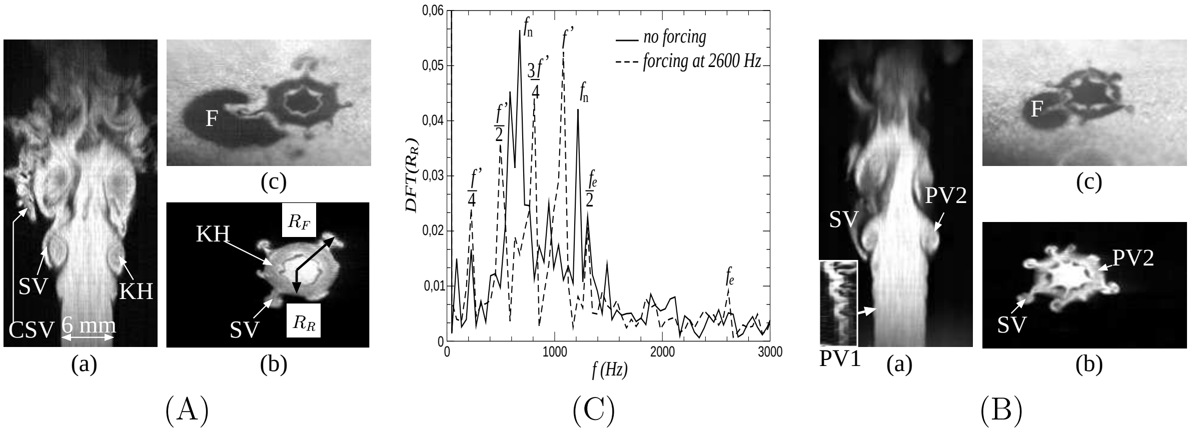
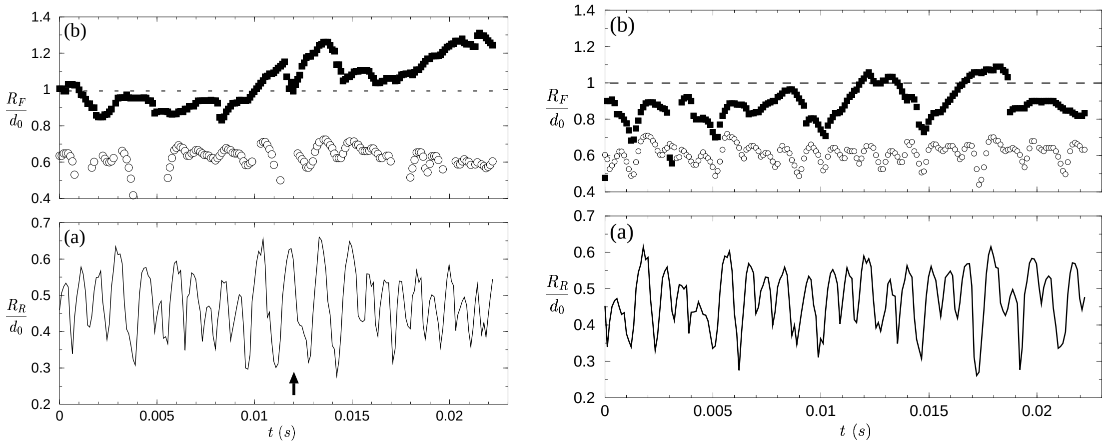


Figure 1: Laser tomography of the unexcited (A) and forced (B) jets. (a) vertical plane with jet seeding. Horizontal planes at the flame base: with (b) jet seeding, (c) air seeding. KH: K-H ring. SV: filament. CSV: connected filaments. F: Flame shape (evaporation of droplets). PV1: forced primary vortex. PV2: paired vortex. (C) R_R Fourier transform.

With no acoustics longitudinal views (Fig.1(A.a)) show that Kelvin-Helmholtz rings form, after an induction zone at $z/d_0 \simeq 2$. Streamwise structures, or filaments, due to secondary instabilities (Lasheras et al. 1986), are more easily identified in horizontal planes (Fig.1(A.b)). There, the jet cross-section is star-shaped (Liepmann and Gharib 1992). Star arms are formed by the matter entrained by streamwise structures. The Fourier transform of the signal of the azimuthal-mean jet radius R_R (see Fig.2(A)), except arms of filaments, at the flame base shows two peaks: the fundamental one ($\simeq$ 1200 Hz) related to the natural mode (f_n) and one sub-harmonic ($\simeq$ 600 Hz) related to the preferred frequency, f_p due to the paired vortex passages (e.g. in Fig.1(C)). The temporal signal of the arms, R_F as those presented in Fig.2(A) indicates two sorts of arms: small arms with $R_F \simeq d_0$ modulated by Kelvin-Helmholtz vortex passages and long arms, generally composed of several connected filaments that can be much longer than 1 d_0. Horizontal tomographic images (Fig.1(A.c)) show that the flame lobes stabilize at the extremity of arms and preferentially at the extremity of the longest arms ($R_F > 1\ d_0$ (Demare and Baillot 2003[b]).



(A) (B)

Figure 2: Temporal evolution of the jet radius: (A) at the flame base (z/d_0=3) for the natural case, and (B) at the flame base (z/d_0=2) at 2600Hz. (a) R_R/d_0: mean jet radius except filaments. (b) R_F/d_0: arm length.

At 2600 Hz, tomographic images seem similar to the unexcited case (Fig. 1(B)). At the flame base, Fig. 2(B), streamwise structures are also present and primary rings have the same size as the natural ones. Nevertheless, primary structures do not classically form from the Kelvin-Helmholtz instability. Because of forcing, small vortices are generated from the burner exit. Around height $z/d_0 \simeq 2$ from which point the natural instabilities begin to dominate the forcing, pairing of the small eddies and the superimposition of the K-H modulation lead to rings whose size is larger than that of vortices which would result only from pairing. Thus, their properties (size, frequency) resemble the natural ones. A non-linear coupling between natural and forced modulations at the flame base, is revealed by the Fourier transform of $R_R(t)$ (see Fig.1(C)): f_n is no longer present while f_e, and $f' \simeq 1$ kHz, a new frequency close to $f_n/2$, are observed with their sub-harmonics. As streamwise structures depend, partly, on the strain induced by primary vortices, this irregular vortex development disturbs the formation of the filaments and their connections that form long arms.

5 Vortex dynamics

PIV measurements are performed to characterize eddy structures (examples of a detailed eddy in transverse planes in Fig.3). In longitudinal planes, cross-sections of both natural and forced filaments show that velocity vectors are oriented at 45^o near the flame location. The velocities at the extremity of the arms of filaments (< 1 m/s) are able to counter-balance the laminar premixed flame propagation ($\simeq 0.4$ m/s) (Demare and Baillot 2001). At the flame base, the forcing does not involve any drastic differences in several features of the dynamics of secondary structures as the scales and rotating velocities of counter-rotating vortices, the mean vorticity. Therefore, as the filament dynamics with acoustics remains similar to that without acoustics, the stabilization mechanism of the lifted flame is unchanged. However, some modifications are noticed between natural and forced primary structure properties. For example, while the values of the Kelvin-Helmholtz vortex vorticity range from 8000 to 15000 s^{-1} in the PDF diagram, at 2600 Hz the vorticity of primary vortices ranges from 6000 s^{-1} to 21000 s^{-1}. This dispersion is mainly due to the disparity of the structures. Consequently, around the flame base, the mean strain rate, $\bar{\Upsilon}$, is lower than the unexcited one. As the development of streamwise vortices depends on the strain rate, the decreases of $\bar{\Upsilon}$ and of the arm lengths are probably linked.

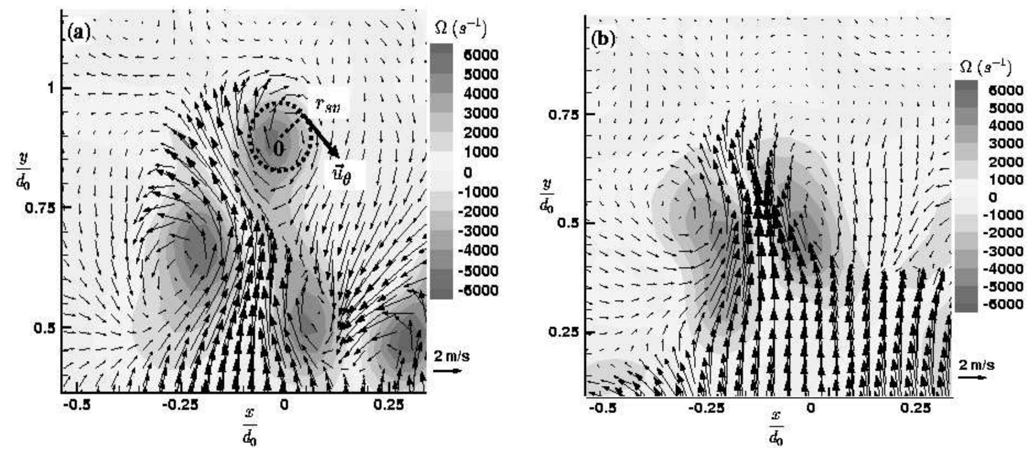


Figure 3: Transverse velocity fields near the flame base, inclined at 21^o from the horizontal plane measured with PIV; the origin coincides with the nozzle center. (a) unexcited case (z/d_0=3). (b) forced case at 2600 Hz (z/d_0=1.8). Gray scale: intensity of vorticity Ω.

6 Mixing by vortices

Transverse tomographic images are used to measure the local oil concentration when only the jet is seeded without flame. The concentration, linked to the Mie scattering intensity quantified on images, gives an evaluation of the mixture fraction $Z(r, \theta, z)$ (more details are given in (Demare and Baillot 2003[c]). From Z, the local flammable area $dA_f(r, \theta, z)$ conditioned by $Z_l = 0.028 \leq Z \leq Z_r = 0.088$ is identified as a function of the position in the jet. The flammable area, $A_f(\mathcal{D})$, in a domain $\mathcal{D}$, is the sum of all $dA_f(r, \theta, z)$ over $\mathcal{D}$. For a given location z, two complementary domains $\mathcal{D}$ are defined. The first domain, $\mathcal{D}^a$, $(0 < r/d_0 < 1)$ characterizes the mixing due to the inner part of the jet, i.e. the axisymmetric part and the small filament ejections. The second domain, $\mathcal{D}^b$, $(r/d_0 > 1)$ takes into account only the long arms. $A_f^a(z)$ and $A_f^b(z)$ are normalized by the corresponding jet areas $A_j^a(z)$ and $A_j^b(z)$ defined in each of the domains. The jet contour is matched with the iso-Z line at Z=Z_l. The parameter A_f/A_j is interpreted as the specific ratio, T_f of flammable mixture in $\mathcal{D}$. Figure 4 presents the mean value of T_f as a function of z. For the inner part of the jet, $\overline{T_f^b}$ is quasi-constant in both cases. The growth of structures is balanced by the increase of the flammable amount. The evolution of $\overline{T_f^b}(z/d_0)$, due to the long filaments, with or without acoustics, shows two distinct parts: a decreasing straight line, s_u; then a quasi-constant part, s_d, about twice (25 %)that of $\overline{T_f^a}$. The decrease of the flammable ratio, s_u, is mainly caused by arm growth. Then, streamwise vortices merge and become disorganized and the mixing induced by them balances the spreading of the ejected matter (line s_d). The intercept of s_u and s_d coincides with the most probable liftoff height. So, for both cases, the flame stabilizes at the position where streamwise vortices develop sufficiently and begin to connect to each other, systematically at 0.5 d_0 from their respective appearances. Therefore, the long arms supply some non-negligible local flammable mixing at their extremity to allow the existence of a partiall

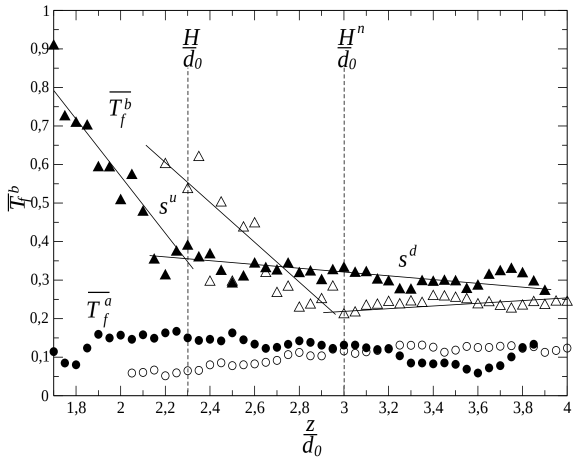


Figure 4: Mean flammable ratios: $\overline{T_f^a}(z/d_0)$ for jet inner part (except long filaments) and $\overline{T_f^b}(z/d_0)$ for long filaments, vs. vertical distance z/d_0. $\circ$, $\triangle$ no forcing. $\bullet$, $\blacktriangle$ forcing at 2600 Hz. The most probable lift-off height of the unexcited case H^n/d_o, of the excited case H/d_o.

7 Discussion and conclusion

Without acoustics, the stabilization mechanism is based on the presence of coherent streamwise counter-rotating vortices which form some arms of ejected matter in transverse cross-sections. With acoustics, the flame stabilization is still due to filaments whose properties (distance between their formation and the flame location, rotating and translating velocities, vorticity, ejection frequencies) are similar to the natural case. But, the primary vortices at the flame base, resembling Kelvin-Helmhlotz vortices, form from pairing of very small vortices generated from the burner exit by the forcing. Such a mechanism of vortex formation alters the development of streamwise structures. Consequently, fundamental changes affect the flame behavior:

- *Its liftoff height is decreased.* The pairing of small forced primary vortices creates structures similar to the natural ones but more upstream; thus, strain conditions, necessary to the development of streamwise vortices and flame stabilization conditions, appear more upstream too.

- *The radius of its base is reduced.* The complex coupling between both forced and natural modulations leads to the formation of primary structures with dispersed properties (frequency, vorticity). Consequently, the strain rate decreases compared to the natural case, and the filaments develop less well and form shorter arms; thus, the flame lobes, stabilized on these arms, are closer to the jet core.
- *The flame is easily reattached* The lengths of the arms fluctuate at low frequencies, because of the non-linear coupling between modulations.Therefore, the stabilization conditions can be temporarily lost; as the flame is closer to the jet core and the burner, the flame can easily go upstream, following the mixing layer, and permanently reattach.

Although the forced jet, at its exit, responds on the axis with the same order of magnitude as the natural turbulence, the effects on the lifted flame are important insofar as its stability is greatly weakened.

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